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Improving Energy Efficiency and Thermal Comfort of Rural Housing in Chile Using Straw Bale Construction

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ABSTRACT

With primary energy imports standing at 80%, principally in the form of fossil fuels, Chile is waking up to the reality of its energy dependency. Equally important is that all but the richest two fifths of the Chilean population can be classed as 'energy poor', and that a large percentage of the Chilean population live during winter in poor hygro-thermal conditions with over 80% suffering problems with condensation and moulds. Balancing energy efficiency with an improvement in living conditions poses a strong challenge for the Chilean government and those of other developing countries.

Straw bales, an affordable, renewable resource, currently burned adding to carbon emission, could provide an answer. The Laboratory of Energy of the Universidad Andrés Bello is currently conducting a research project DI-05-09JM, funded by the Dirección General de Investigación of the Universidad Andrés Bello, to test this hypothesis. This paper will discuss their findings to date.

THE CURRENT SITUATION

Energy Dependency and the Chilean Energy Crisis

Faced by a severe energy crisis in 2008 Chile has begun to question its energy dependency. Despite being a country rich in renewable energy sources, development of the necessary technologies to harness these has been slow and for the foreseeable future Chile will continue to depend on the importation of its primary energy sources. Official figures report that in 2006 80% of primary energy was imported. Of this 15% was coal, 48% crude oil, 16% petroleum based products and 20% natural gas [www.iea.org; IEA 2006]. Chile is not alone in this problem, and if we consider Hubbert's 'Peak Oil' Theory [Hubbert 1982], it would appear clear that that the world must increase its energy efficiency at the same time as looking for new renewable sources of energy. It has been estimated that by 2025 energy efficiency could reduce the overall predicted energy demand in Chile by around 20% [PRIEN 2008].

Climate Change

Coupled with the question of energy dependency, we must also consider that the majority of Chilean primary energy sources are emitters of greenhouse gases. It is now a widely accepted fact in the international scientific community that increased emissions of greenhouses gases are the principal cause of climate change. According to the report 'CO2 Emissions from Fuel Combustion 2009' of the International Energy Agency, between 1990 and 2007 Chile saw an estimated increase of 117.4% in emissions of greenhouse gases from fuel combustion [IEA 2009].

Energy Poverty

The concept of 'energy poverty' was defined by Lewis (1982) and revised by Healy (2004) as "The inability to heat ones home to an adequate (safe and comfortable) temperature owing to low income and poor (energy inefficient) housing" and is applicable to households that need to spend more than 10% of their annual income on fuels in order to achieve satisfactory indoor comfort [Healy 2004]. In Chile a report on the annual outgoings on fuel when firewood is included, indicates that in 2006 all but the richest two fifths of the Chilean population could be classed as energy poor [Márquez and Miranda 2007]. In addition a study by the Programa País Eficiencia Energética and the German technical Cooperation GTZ showed that a large percentage of the Chilean population live during winter in poor hygro-thermal conditions with over 80% suffering problems with condensation and moulds [CNE and GTZ 2008]. This problem is further exasperated by high usage of freestanding, naked flame, liquid gas or paraffin heaters, or inefficient wood burning stoves.

Typical construction techniques in rural central Chile

Although the historical construction technique of Northern and Central Chile is predominately that of Adobe (unfired clay and straw bricks), currently it would appear that in rural central Chile timber construction is more prevalent.

To confirm these general perceptions of what constituted typical construction in the central valley, a survey of a typical rural village, Rungue 50km north of Santiago, was undertaken.

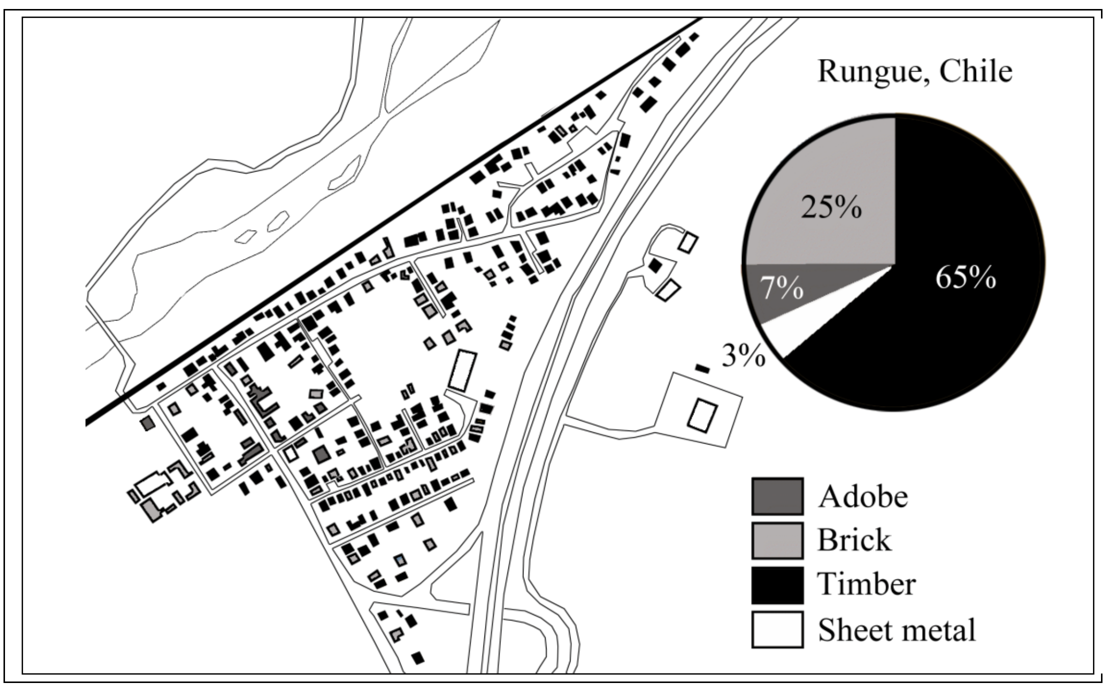

Fig. 1. Survey of Typical Construction in a Rural Population, Central Chile

Following this study it was concluded that the most prevalent construction technique was that of timber framing clad with a single layer of ship-lapped timber siding, panels of MDF or panels of other timber derivatives. In many cases, especial in the houses of those with limited resources, these walls are un-insulated with no internal finishing. Assuming a 15mm thickness of timber siding this would provide a U-value of 3,5W/m^{2}K. In November 2006 the Chilean government introduced a new thermal building regulation that requires a u-value of at least 1.9W/m^{2}K [Instituto de la Construcción 2006] for dwellings in the 3rd thermal zone, which covers central Chile including the capital Santiago where 40% of the Chilean population is concentrated. The regulation however only applies to new constructions and does not cover the timber clad, timer frame, temporary housing known as 'mediaguas' currently being built by charities with the aim of eradicating the shantytowns.

Housing the Homeless

According to the National Survey of Shantytowns undertaken by the charity 'Un Techo para Chile,' in 2007 there existed in Chile 533 shantytowns (campamentos) housing 28,578 families. Of which 46% were located in the central zone (5th, 6th and Metropolitan Regions). [CIS Un Techo para Chile 2007] With its objectives of eradicating these slums by 2010 'Un Techo para Chile,' along with other charities and government agencies, has a commitment to providing definitive housing that meets with the Chilean building regulations. However in the short term the answer to re-housing the homeless is often met with the construction by volunteers of timber framed, timber clad 'mediaguas.' These one-roomed temporary structures have an approximate cost of US$540. Whilst they provide an improvement on the often unsafe and unsanitary, self constructed shanty dwellings, the offer little improvement in hygro-thermal comfort or energy efficiency.

Therefore balancing energy efficiency and the reduction of greenhouse gas emissions, with an improvement in living conditions poses a strong challenge for the Chilean government and those of other developing countries.

COULD STRAW BALES OFFER A SOLUTION?

Turning waste into efficient housing

In Chile in the agricultural productive year 2008-2009- 281,000 hectares were planted with wheat, 101,000 with oats, 18,500 with barley and 24,000 with rice. [www.odepa.gob.cl 2009] This equates to 0.02 hectares per capita of cereal crops. In comparison, the same year in the UK approximately double the amount 0.05 hectares per capita of cereals were planted. [DEFRA 2009] Currently in Chile the straw from these cereal crops is viewed as a waste product and is burnt in the fields, further adding to carbon emissions and poor rural air quality. The straw from all these crops could be used for straw bale construction, thereby reducing green house gas emissions at source and potentially, as we will see later in this paper, emissions arising from heating rural dwellings. In addition, the majority of cereal production is concentrated in the central zone of Chile, where as we have seen 46% of the families currently living in shanty towns are located. If divided by this number of families, the area of straw producing cereal crops per family would equate to 32 hectares.

Whilst the use of straw, or grasses, in construction dates back thousands of years, perhaps as far back as the first human constructions, the first recorded use of straw bales in construction began in the Sand Hills region of Nebraska in the late 19th century. Faced by a shortage of other suitable building materials the settlers of the area turned to the product of the newly invented mechanical baler. These early constructions used the bales in a load bearing fashion with no additional structural members. To this day structurally load bearing straw bale constructions are referred to as Nebraska-style.

Although the most straightforward form of straw bale construction, load bearing or Nebraska-style bale structures present some restrictions and difficulties. These include limitations in opening sizes and maintaining walls and corners plumb. In addition there exist concerns over seismic stability despite Californian tests that have proved good resistance to seismic loading by straw bales encased in steel mesh and cement render. For these reasons some degree of timber structure would appear to be an advantage. To date the research team has experienced a greater acceptance of their proposals when describing a 'timber framed house with straw bale insulation infill' rather than a 'straw bale house.'

Straw filled timber structural components

Bearing in mind that the majority of rural housing is self-built or built by volunteers in the case of temporary social housing, construction solutions need to be simple and where possible prefabricated. The straw bales themselves already constitute a prefabricated module of convenient size and proportions. Their size and weight is at the limit that can be safely handled by one person. For this reason larger prefabricated modules incorporating more than one bale were discounted. However in the case of the vertical structural members a prefabricated element was designed. This consists of two 2"x3" vertical softwood uprights joined top and bottom by horizontal 2"x3" battens, backed by a sheet of medium density fibre board (MDF) which in itself is a waste product from the printing industry. The space between the two uprights is filled with loose straw held in place by wire mesh (chicken wire). These elements can be prefabricated and can be manoeuvred by one person.

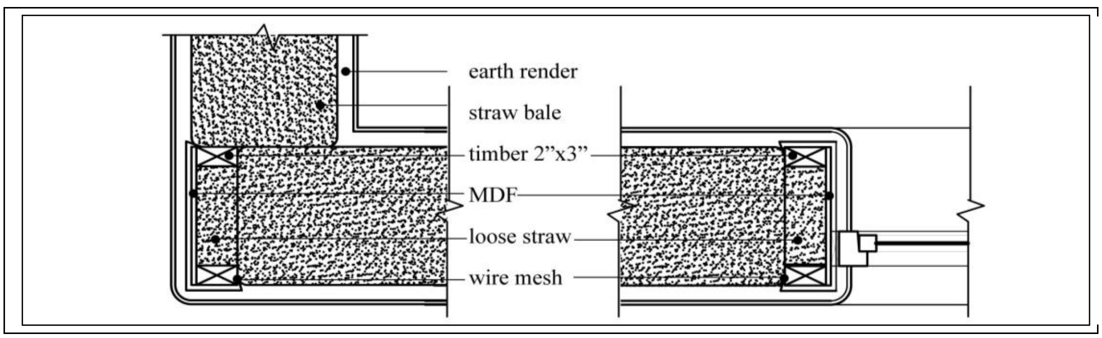

Fig. 2. Plan of Prefabricated Elements at Corner and Window Detail

THERMAL PROPERTIES OF STRAW BALES

Laboratory test results to date

Since the initial investigations that formed the masters thesis project of Joe McCabe at the University of Arizona [Stone 2003], there have been numerous tests performed to ascertain the thermal properties of straw bales. Not surprisingly for a natural material these results vary considerably with coefficients of thermal conductivity (lambda) between 0.034 [Wimmer et al. 2001] and 0.15W/mK [Stone 2003], and U-values between 0.103, and 0.334W/m^{2}K see table 1. For those aiming for zero carbon or energy positive buildings these discrepancies might be worrying. However when you consider that the current thermal building regulations for central Chile can be met with walls of 1.9W/m^{2}K, even the worst result for straw bale would be five time better.

Table 1. Results of International Thermal Conductivity Testing of Straw Bales

Author	Date	Location	Method	Straw Type	Bale dimension	Moisture content %	Density kg/m^3	U Value W/m^2K	λ W/mK
McCabe, J.	1993	University Arizona	Guarded hot plate. Single bale	Wheat	580	8.4	133	0,103	0,054edge 0,061flat
Acton, R.U.	1994	Sandia Labs	Thermal Probe Single Bale	Not listed	460	Not listed	83.3	0,118	0,05 flat
Watts, C., Wilkie, K., Thomson, K. and Corson J.	1995	Nova Scotia	Hot plate, in-situ	Not listed	460	Not listed	Not listed	0,2	0,097
Not listed	1996	Oak Ridge National Lab	Hot Box full wall	Wheat	460	20	112	0,334	0,15
Not listed	1997	CEC	Hot Box full wall	Rice	580	11	107	0,218	0,13
Stone, N.	1997	Architectural Testing Labs-Fresno	Hot box	Not listed	580	Not listed	Not listed	0,218 0,172	0,13- 0,07
Not listed	1998	Oak Ridge National Lab	Hot Box Full wall	Not listed	480	13	128	0,208	0,099
Wimmer, R.	2001	BMVIT, Vienna	ISO 8301	Not listed	Not listed	Not listed	Not listed	Not listed	0,038
Wimmer, R.	2001	BMVIT, Vienna	ÖNORM B6015	Not listed	Not listed	Not listed	Not listed	Not listed	0,034
Andersen, J.M. and Andersen, B.M.	2004	Statens Byggeforskni-ngsinstitut, Denmark	Hot box, Single bale	Not listed	385 365	Not listed	75 90	0,208- 0,196	0,057-0,060 0,052 flat, -0,056 edge
Goodhew, S. and Griffiths, R.	2004	University of Plymouth	Thermal probe	Not listed	360	Not listed	60	0,18	0,067
Not listed	2006	Deutsches Institut für Bauttechnik	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	0,08 flat 0,052 edge

EVALUATING THE POTENTIAL OF STRAW BALE

Results of thermal simulation using TAS software

Using the environmental computer simulation software TAS, three test chambers of equal internal dimensions and orientation were simulated. The first un-insulated, of timber framed construction clad in timber siding; the second the same but with sufficient expanded polystyrene to comply with Chilean thermal building regulations; and the third with walls constructed of 360mm straw bales on edge with 30mm of earth render both externally and internally applied. An averaged coefficient of thermal conductivity of 0.8 W/mK was used for the straw bale. Examples of the results of this simulation can be seen in figures 3 and 4.

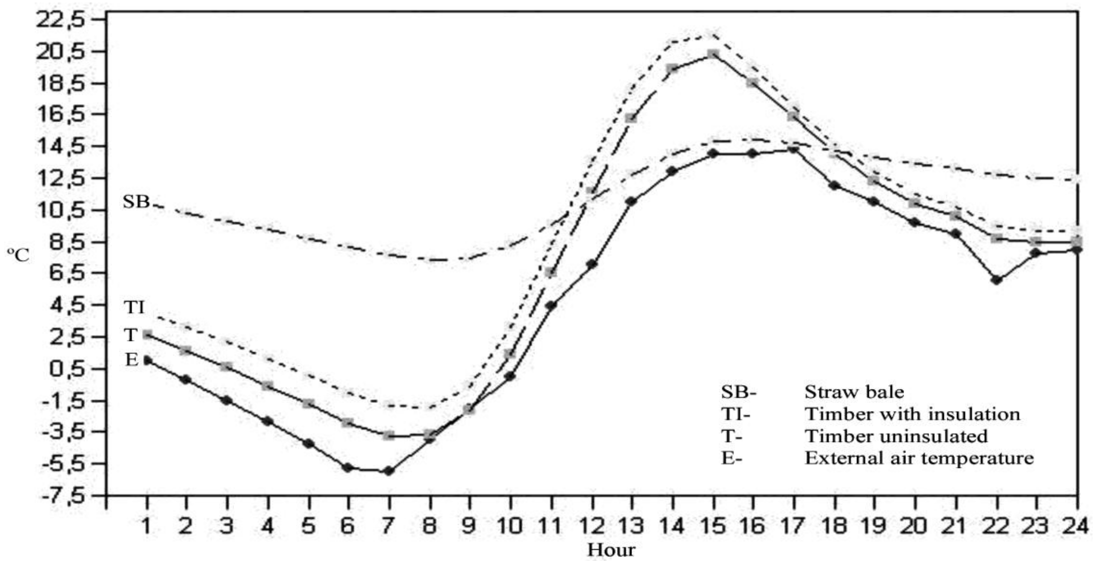

Fig. 3. Dry Bulb Temperatures 31st July (winter) simulated with TAS software

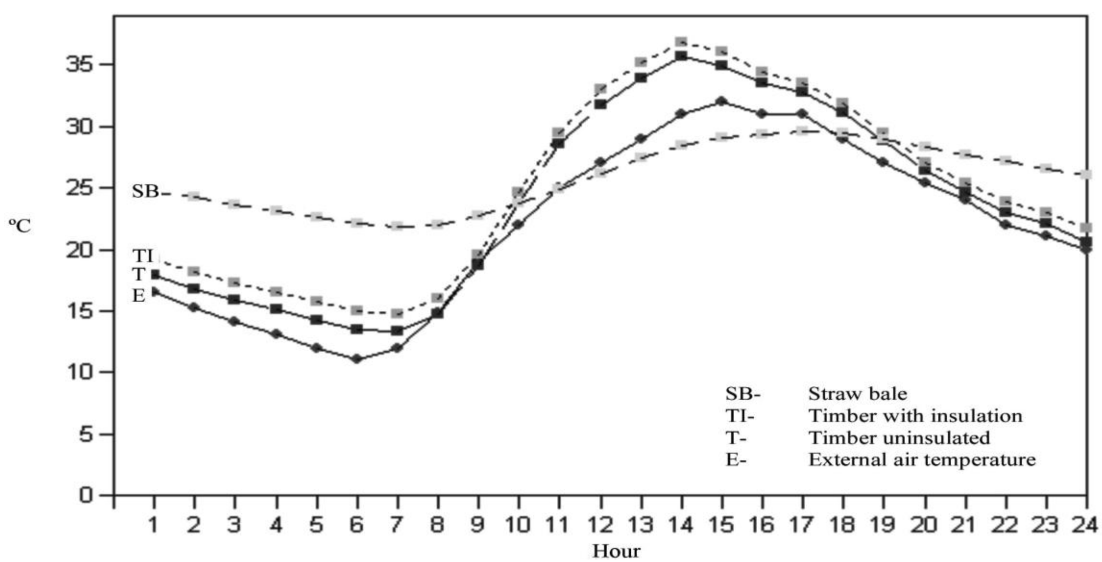

Fig. 4. Dry Bulb Temperatures 2nd February (summer) simulated with TAS

From the results of the simulation it can be seen that the internal dry bulb temperatures for the straw bale test chamber are far steadier than those of the chambers of timber construction. However peak temperatures during the summer rise above comfortable levels during the middle of the day. The team has considered cross ventilation, ventilated roof void and increased insulation at ceiling level as possible solutions to this problem. It is also interesting to note that with the particular climate, that of central Chile, a lighter weight structure provides better thermal comfort in the middle of a sunny winter day. This advantage is outweighed by large thermal losses by the timber chambers during the cold nights and occasional overcast day, but it highlights that passive or active solar gains should be considered in final architectural designs.

Cost comparison of Straw Bale and Typical Construction

Building costs were calculated for the same test chambers described above that were simulated in TAS. Prices were based on those of the local construction supplier, except for the straw bales, for which three separate quotes were obtained from suppliers in the local area. Labour costs were not included assuming self-build or construction by volunteers. The three prices for straw bales received were per bale $1,000 Chilean pesos, $1,500 Chilean pesos and $2,000 Chilean pesos, giving an average value of $1,500 or US$2.70. Prices calculated for the test chambers, internal dimensions 2480x1580mm, are displayed in table 2.

Table 2. Cost Calculation for Test Chambers

Construction type	**Overall cost US$***	**Cost per m^2 net area US$***
Straw bale 360mm; timber, straw filled, structural elements as described earlier; 30mm earth render (both sides); lime wash; *single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt*	548	140
Timber structure consisting of 2"x3" softwood timbers; softwood timber siding 15x125mm; white exterior emulsion paint; *single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt*	555	142
Insulation- expanded polystyrene; **Timber** structure consisting of 2"x3" softwood timbers; softwood timber siding 15x125mm; white exterior emulsion paint; *single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt*	631	161
* exchange rate at date of writing- US$1=$554,700 Chilean pesos *Materials in italics are common to all three test chambers*		

According to these calculations it would appear that the material costs for the straw bale construction are fractionally less than the typical construction.

CONCLUSION

From the findings of this paper we can conclude the following:

- In aiming to meet the existing housing demand, Chile should consider not only the provision in terms of quantity but also an improvement in the quality of social housing. This is especially true with respect to the energy efficiency of the dwellings, considering Chile's high energy costs, both economic and environmental, and the low wages of their inhabitants. By improving the energy efficiency and the hygro-thermal conditions of social housing it would be possible to improve the health of the inhabitants whilst reducing the countries energy demands and emissions of greenhouse gases.
- 46% of the demand for new social housing is in the central zone of Chile which coincides with the agricultural area producing cereal crops. Based on the agricultural productive year 2008-2009 there exists a potential 32 hectares of straw per homeless family located in this region.
- International research to date shows that whilst the thermal conductivity of straw varies considerably, high levels of thermal insulation can be achieved with typical bale walls achieving u-values between 0.103 and 0.334W/m2K., values that are far in excess of the current legal requirement of 1,9W/m2K.
- When coupled with the use of an earth render to provide thermal mass, simulation of indoor temperatures suggest that a stable temperature can be maintained both in summer (21.5-26.8°C) and winter (7.9-15.7°C). However without the improvement of other building elements such as windows, doors, and roof build-up, the temperatures are such that heating will still be required in winter.
- Construction costs of walls of straw bales infilling a timber structure, considering purely material costs, are fractionally less than those of typical un-insulated timber framed, timber clad walls (US$2 less per m²) and considerably less than those of insulted timber frame, timber clad walls (US$11 less per m²)

It could therefore be concluded that straw bales could possibly provide affordable energy efficient rural housing that have improved internal thermal comfort conditions, whilst using a waste product that is currently burnt.

FURTHER RESEARCH

Proposed physical testing

In order to confirm the results obtained in the computer simulation three physical test chambers are currently being constructed. These are of the three construction types detailed in table 2. During the period of one year the internal and external temperatures and relative humidity will be monitored with Logtag HAXO-8 temperature and humidity recorders.

Fig. 5. Construction of physical test chambers, progress January 2010

Compilation of International Straw Bale building codes, fire and seismic testing

To date the team's research has focused on the availability, cost and thermal performance of straw bale construction. Through their study the team is aware that there exists a wide range of national and state (USA) building codes for straw bale construction, and that research has already been undertaken to define its fire and seismic resistance. During the one year period of the physical testing of the test chambers, the team will work compiling this information and summarising it in Spanish. It is hoped that armed with this information and the final conclusions of this research project DI-05-09JM, government funds can be sought to undertake a pilot project of energy efficient social rural housing, using straw bale construction.

REFERENCES

Andersen, J., M., Andersen B., M., (2004) *Straw Bale Houses design and material properties*, Danish Building and Urban Re-search, Statens Byggeforskningsinstitut, Denmark,

APEC Energy Working Group (2009). *Peer Review on Energy Efficiency in Chile,* <http://www.ppee.cl/admin/archivo_arc_binario_bv.php?key=89>

Bergeron, M. and Lacinski, P. (2000). *Serious Straw Bale, A home construction guide for all climates.* Chelsea Green Publishing Company, Vermont

Commins and Stone. (1998). *Tested R-value for Straw Bale Walls and Performance Modeling for Straw Bale Homes.* California Energy Commission.

Centro de Investigación Social (CIS) Un Techo para Chile (2007), *Catastro Nacional de Campamentos 2007 (National Survey of Shantytowns 2007),* Santiago de Chile

Department of the Environment Food and Rural Affairs. (2009) *Cereals And Oilseed Rape Production Estimates: 2008 Harvest,* United Kingdom-Final Results, London

Goodhew, S and Griffiths, R. (2004) *Sustainable earth walls to meet the building regulations,* Energy and Buildings 37 (2005) 451–459

Hubbert, M.K. (1982). *Techniques of Prediction as Applied to Production of Oil and Gas*, US Department of Commerce, NBS Special Publication 631.

Healy J.D. (2004) *Housing, fuel poverty, and health: A Pan-European Analysis*, Ashgate Publishing, Ltd., England

Instituto de la Construcción (2006). *Manual De Aplicación Reglamentacion Termica Minvu Ordenanza General De Urbanismo y Construcciones, Articulo 4.1.10*, Santiago de Chile. <http://www.mart.cl/html/manual.html>

International Energy Agency, (2006) Energy Balance Statistics, Chile <http://www.iea.org/Textbase/stats/balancetable.asp?COUNTRY_CODE=CL>

International Energy Agency, *(2009) CO2 Emissions from Fuel Combustion 2009* <http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=2143>

Márquez, M. Miranda, R. (2007) *Una estimación de los impactos en los presupuestos familiares derivados del sostenido aumento en los precios de la energía*, Universidad Austral, Chile

Oficina de Estudios y Politicas Agrarias, Estadísticas de superficie sembrada de cultivos anuales, Santiago 2009 <http://www.odepa.gob.cl>

PRIEN, Programa de Estudios e Investigación en Energía, (2008*) "Aporte Potencial de: Energías Renovables No Convencionales y Eficiencia Energética a la Matriz Eléctrica, 2008-2025"*. Universidad de Chile, Universidad Técnica Federico Santa María, Chile, <http://www.prien.cl/documentos/> 69 pages

Proyecto Fomento de la Eficiencia Energética (CNE/GTZ) (2008) *Determinación de línea base "anual" para la evaluacion de la inversion en eficiencia energetica en el sector residencial invierno 2007 – verano 2008*, Santiago de Chile

Stone, N. (2003) *Thermal Performance of Straw Bale Wall System*, Ecological Building Network, <http://www.ecobuildnetwork.org/pdfs/Thermal_properties.pdf>

Wimmer R., Hohensinner H., Janisch, L., and Drack, M. (2001) *Heat Insulation Performance of Straw Bales and Straw Bale Walls*, GrAT - Center for Appropriate Technology / Vienna University of Technology